PULSED POWER HYDRODYNAMICS: ATLAS RESULTS AND FUTURE PERSPECTIVES

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Abstract

Pulsed Power Hydrodynamics (PPH) is a new application of low-impedance, pulsed power technology to the study of complex hydrodynamics, instabilities, turbulence, and material properties in a highly precise, controllable environment at the extremes of pressure and material velocity. The Atlas facility, designed and built by Los Alamos, is the world's first, and only, laboratory pulsed power system designed specifically to explore this relatively new family of pulsed power applications. Constructed in the year 2000 and commissioned in August 2001, Atlas is a 24-MJ high-performance capacitor bank delivering currents up to 30-Megamperes with a rise time of 5 to 6-µsec. The high-precision, cylindrically imploding liner is the tool most frequently used to convert electromagnetic energy into the hydrodynamic (particle kinetic) energy needed to drive strong shocks, quasi-isentropic compression, or large volume, adiabatic compression for the experiments. At typical parameters, a 30-gr, 1-mm-thick liner with an initial radius of 5-cm, and an intermediate current of 20-MA can be accelerated to 7.5-km/sec producing megabar shocks in medium density targets. Velocities up to 20-km/sec and pressures >20-Mbar in high density targets are possible.

The first Atlas liner implosion experiments and 16 application experiments were conducted in Los Alamos between September 2001 and September 2002. Beginning in October 2002 Atlas was disassembled, moved to the Nevada Test Site, and re-commissioned in July 2005. The Atlas experimental program at the NTS comprised 10 application experiments beginning in July 2005 and ending in May 2006.

This paper will summarize some of the results of the first Atlas experimental series at the Nevada Test Site. The 2006 series included two implosion dynamics experiments, two experiments exploring damage and material failure to complement an on-going series of pulsed-power-driven Damage experiments conducted jointly with VNIIEF in Sarov, a new advanced hydrodynamics series aimed at studying the behavior of damaged material ejected into a gas from a shocked surface; and a new series exploring friction at sliding interfaces under conditions of high normal pressure and high relative velocities[1].

Longer term applications of Atlas may include continuation of the experimental series already begun and closely related efforts such as the exploration of material strength at high strain rate. However, work on more basic problems including the study of material interfaces subjected to multi-megagauss magnetic fields, the properties and behavior of strongly coupled plasmas; the equation of state of materials at pressures approaching 10-Mbar, and magnetized target fusion concepts can also be considered.

While Atlas continues to be the only laboratory facility specifically designed to pursue Pulsed Power Hydrodynamics concepts, other platforms including explosive pulsed power systems and smaller scale systems that can bring the advantages of pulsed power drive to experiments conducted with other advanced diagnostics such as proton-radiography and other advanced accelerator techniques are also being explored.

I. INTRODUCTION

Pulsed Power Hydrodynamics (PPH) is among the newest applications of pulsed power technology to emerge from the steadily advancing field of electrical energy storage and power conditioning. These advances have resulted in increased power and energy, but also in improved reliability, reproducibility, and economy. The evolution of pulsed power hydrodynamics has been shaped by the need for high precision experimental data to validate the sophisticated, numerical models used in modern computer simulations and to improve the physics in those models. Without question, the development of pulsed power hydrodynamics has been aided by the

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development of a variety of working platforms over the last 50 years[2]. Using these platforms, pulsed power hydrodynamics has, in less than a decade, helped validate existing physics model and enabled empirical experimentation leading to the development of the new models, thereby increasing the community's confidence in the results of the computer simulations that are, increasingly, replacing field testing in many disciplines.

II. REQUIREMENTS FOR PULSED POWER HYDRODYNAMICS

Innovation is usually driven by specific, but frequently diverse requirements. This is, of course, true of pulsed power technology where the electric utility industry, new manufacturing concepts, magnetic and inertial confinement fusion programs, along with innovative confinement projects and efforts to develop intense neutron sources have all shaped the development of pulsed power technology over the last half century.

Advanced, non-nuclear defense applications such as directed energy; homeland defense through a variety of approaches to active interrogation, microwave and rf applications; electromagnetic projectile acceleration, and special operations applications have similarly shaped the field.

In the area of nuclear weapons science and technology, high peak power systems were needed to power a variety of simulators for nuclear weapons effects; the hot dense plasmas forming soft x-ray sources; electron accelerators for producing harder x-rays; and linear induction accelerators for fundamental investigations in nuclear and elementary particle physics.

Joining these plasma and beam applications was the recently emerging use of low impedance, very high current pulsed power sources for material properties studies at pressures and temperatures otherwise inaccessible, and for the study of advance high energy density fluid dynamics, implosion dynamics, and fluid instabilities at extreme conditions.

Among the nuclear weapon science activities called Stockpile Stewardship, experimentally-based development, test and evaluation in the form of underground nuclear testing has been replaced by numerical simulation-based system certification with calculations performed on the best computer hardware with best physics models available. New experimental techniques expanding the parameter space in which high precision, reliable, and reproducible data is conveniently and economically available is essential for "validating" the physics models used in modern simulations. Pulsed power approaches to enabling such fundamental experiments play a crucial role, now, and in the future.

Pulsed power hydrodynamics uses magnetically driven, ultra-high-precision implosions to conduct sophisticated experiments in condensed matter. The conventional

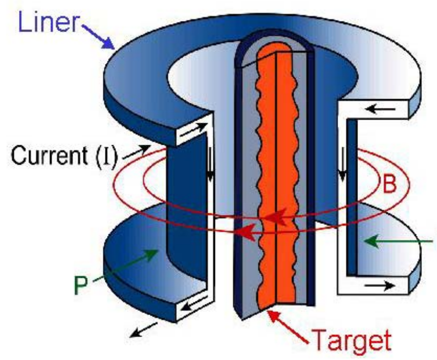

Figure. 1. Z-pinch Liner implosion geometry

z-pinch implosion (Fig. 1) is the configuration most frequently used to convert magnetic energy to particle kinetic energy. In this geometry, 10 to 100-gram aluminum liners are smoothly and uniformly imploded by the magnetic field produced by 10's of MA currents delivered from an ultra-low impedance, microsecond pulsed power source. The imploding liner, with its several megajoules of kinetic energy, can be applied in several applications (Fig. 2) including accelerating the liner to relatively high velocity before impacting a target to produce intense shock pressures of 100's of kbar in light materials and several Mbar in high density materials. The liner can similarly be used to apply the magnetic pressure directly to a sample to achieve quasi-isentropic compression of the sample without shocks—and without the complication of magnetic fields penetrating to the sample. Similarly, the liner can perform significant P-dV work on a fluid, converting liner kinetic energy into

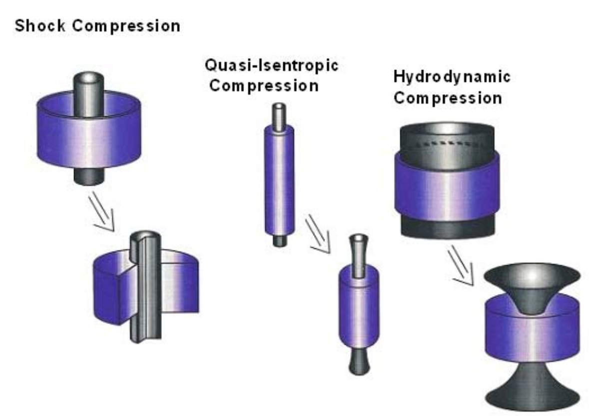

Figure 2. Magnetically imploded liners can be used to produce a variety of useful hydrodynamic environments.

internal energy in the compressed gas, plasma, or magnetized plasma, heating and compressing the fluid in times relatively short compared to energy loss times.

While some of the advantages of high speed, high precision cylindrical implosions can be achieved in other ways (such as by cylindrical implosions directly driven by high explosives), magnetically driven implosions offer a number of unique advantages:

- Magnetic fields are transparent to visible light and to x-rays, making the evaluation of target behavior with imaging diagnostics much easier by, for example, eliminating the attenuating and contrast-reducing effects of the HE products.
- Magnetic fields are fundamentally cylindrical, exactly matching the basic geometry of the experiment and complementing the planar capability of high performance gas guns. Uniform, cylindrical implosion geometries deliver the multi-dimensional effects of converging systems while retaining with both axial and transverse (radial) diagnostic access.
- Magnetic field drive is "dialable," controllable, and reproducible. The setting of one experimental parameter permits the adjustment of drive energy and hence implosion velocity and energy. A factor of 5 change in operating parameters results in a factor of 25 change in operating pressure. Additionally, better than 1% control and reproducibility has been demonstrated.
- Magnetic field drive is immediately adaptable to large (cm-scale) targets complementing, though at lower velocity, the very high energy density drive available from high energy lasers on mm- and sub-mm-size targets.
- Magnetic fields can provide high explosive-like shock pressures without shocks, thereby providing access to states of matter not accessible on the principle Hugoniot, complementing traditional HE driven equation-of-state techniques.
- Magnetic fields deliver energy at the speed of light without accompanying mass, providing fundamentally faster velocities than can be achieved with HE or gas guns where the sound speed in the driving fluid sets the upper limit of energy delivery to the working package. Energy delivered masslessly gives rise to much less collateral impulse imposed on the surroundings, making confinement and, if necessary, complete containment, of experimental materials easier.
- Magnetic fields can be removed almost instantly, by switching systems, allowing delivery of only the required amount of energy—and no more—enabling good sample recovery for post-shot analysis
- Energy for magnetic drive can fundamentally be stored (e.g., in capacitors) that are remote from the experiments enhancing overall safety of operations involving hazardous materials.

III. PULSED POWER CAPABILITIES MADE POSSIBLE THE DEVELOPMENT OF PULSED POWER HYDRODYNAMICS

The pulsed power community, world-wide, has developed an impressive ensemble of capabilities (facilities and fieldable systems) that support pulsed power hydrodynamics activities and that have made possible the development of the new discipline. The development of many of these capabilities preceded the formal establishment of programs now known as pulsed power hydrodynamics and the history of this development has been reviewed elsewhere.

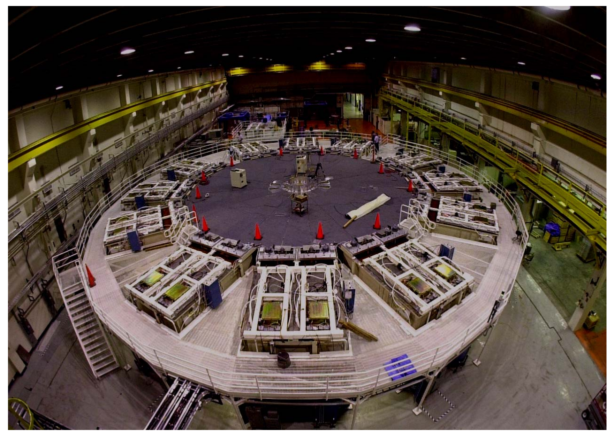

Figure 3 Atlas facility at Los Alamos.

Among all the capabilities developed around the world in the last 5 decades, that have significantly advanced the discipline of pulsed power hydrodynamics, Atlas is the first, and only, pulsed power system specifically optimized for driving PPH experiments (Fig. 3)[3]. It is, also, the world's newest, ultra-low impedance, high-current capacitor bank facility, and is the flagship facility for PPH experiments, in addition to offering capability for a variety of other basic physics investigations

Conceptual development for Atlas began in 1992. Component selection, development, and testing continued through 1996, when the final configuration was selected and engineering design begun. Construction began in late 1999, and assembly was completed in August 2000. Atlas passed its pulsed power acceptance tests in December 2000, and achieved operational status after a series of pulsed power characterization tests in August 2001. Atlas was operated at Los Alamos until late 2002[4]. It was then disassembled and reassembled at the Department of Energy's Nevada Test Site (NTS) where it was re-commissioned in July 2005. Pulsed power hydrodynamics experiments began on Atlas in the same month, and continued through June 2006.[5]

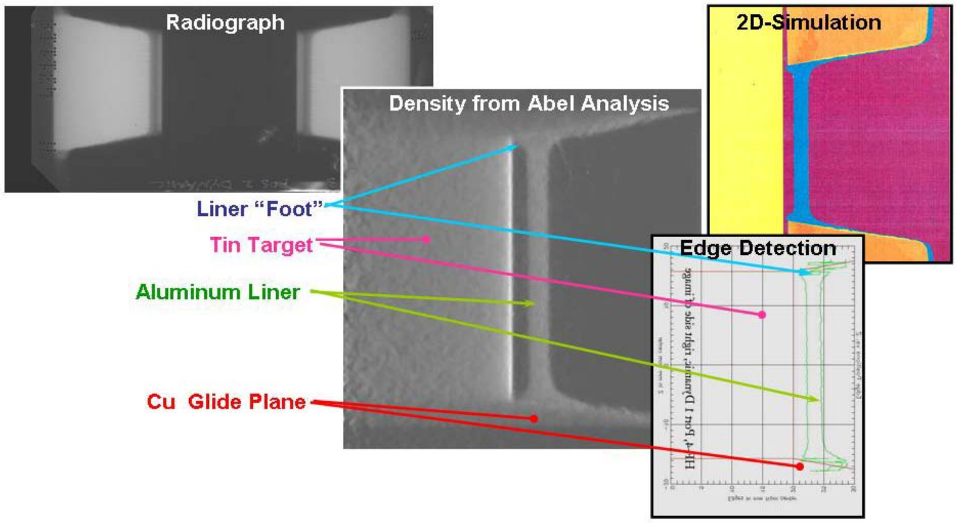

Figure 4. Improved radiographic techniques allow detailed comparison of liner implosion experiments with 2D-MHD simulations, exploring behavior at the contacts.

IV. LINERS

To support any of the family of PPH applications: shock production; quasi-isentropic compression; or adiabatic compression requires high performance liners and most applications require high precision as well. While both the Z-pinch and the Θ-pinch configuration have been explored for solid liner implosion applications, the z-pinch geometry was chosen for PPH applications in part for ease of modeling with existing 2D MHD codes; in part because of the perceived difficulty in eliminating the "feed slot perturbation"; and in part to avoid the inefficiency of the long-coil geometry.

Steady improvement in power flow geometries, in liner designs, in fabrication techniques, and especially in radiographic diagnostics (Figure 4) accelerated the development of ultra-high precision liner implosions and development of the diagnostic techniques used to evaluate those implosions[6]

With the improvement in radiographic diagnostics, came more detailed assessment of the behavior of the magnetic field / metal interface where the aluminum liner is heated by the driving current which can be 10's MA in some cases. As magnetic fields at the interface approach 1 MG during the early stages of the implosion (exceeding 1MG in the later stages) the surface of the aluminum conductor is at least melted, in many case spending part of its life in the region of mixed two phase composition under the vapor dome. Under these conditions, the interface between the mass-less magnetic field and the strength-less aluminum liquid or (two phase) fluid is susceptible to fluid instabilities, specifically the acceleration-induced Rayleigh-Taylor instability. Such instabilities are regularly observed even in cases where parameters are chosen to insure that the inner part (>50%) of the liner is unmelted. Part of the liner is designed to remain unmelted with the objective of retaining some material strength and to, thereby, inhibit some of the unstable behavior

While the growth of perturbations at such an unstable interface is well understood, analytically; and thoroughly validated experimentally in cases where material strength is absent, development of the high precision imploding liner calls for a similar understanding of instability behavior in systems where, for example, a outer, melted fluid layer accelerates an inner, unmelted, strength bearing layer. A series of early experiments using the Pegasus system at Los Alamos imposed pre-formed (machined) sinusoidal perturbations on the outer aluminum liner surface to seed the growth of single wavelength perturbations[7]. Radiographic images following the growth of the perturbations, Abel inverted and displayed as azimuthally symmetric density were compared with analytic estimates of the threshold (in acceleration) for the onset of perturbation growth in strength bearing liner material (Figure 5). Growth of the perturbations in the later stages of the implosions were similarly compared with 2D MHD simulations where elementary (strain rate independent) models of material strength in the unmelted parts of the liner were employed. Good agreement, for single wavelengths, was found for both the threshold for onset of growth of the perturbations, for growth during the intermediate period where both a strong layer and a strengthless fluid layer are present and finally in the later stages of the implosion when the liner is nearly fully melted and where the familiar, analytic, measures of fluid growth should apply.

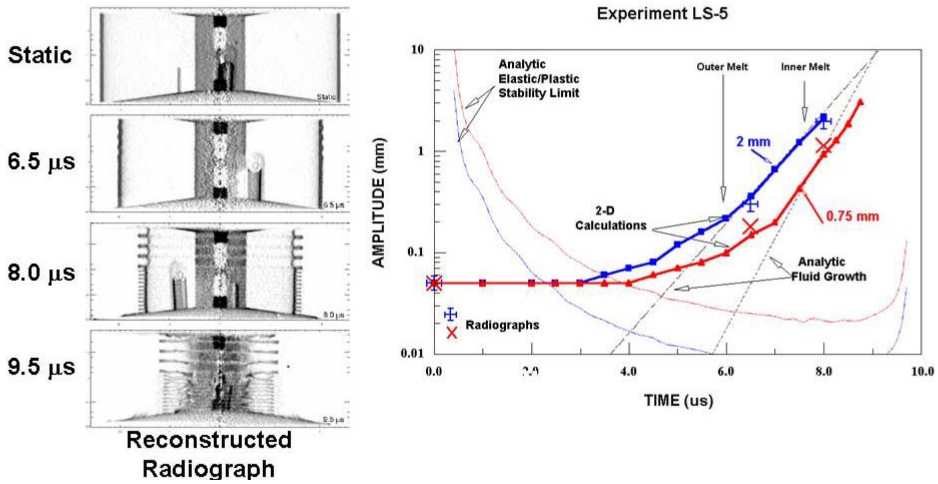

Figure 5. Preformed, single wavelength perturbations were imposed at the liner/field interface to validate both analytic models and the results of direct numerical simulation describing liner implosions.

Experiments to validate the overall (center of mass) dynamics of the motion of condensed liners were conducted on Shiva Star, Pegasus and Atlas with the most detailed combination of radiographic imaging and VISAR (Velocity Interferometry for Surfaces of Any Reflectivity, ie. laser interferometry) diagnostics applied to the most recent (2005) Atlas experiments conducted at the DOE Nevada Test Site. VISAR measurements of the velocity of the inner surface of the liner provides excellent trajectory data to compare against zero, and one dimensional simulations of implosion dynamics. For these experiments, liners with 1.4-mm thick liner walls, with initial outer radius of 5 cm and height of 4 cm were imploded with peak currents of 18.5 MA, reaching peak implosions velocities of 4 mm/μsec as the liner approached the central diagnostic unit (which holds the VISAR diagnostic hardware. Liner implosion dynamics are among the more sensitive tests of driver circuit models and these liner dynamics experiments form a relatively

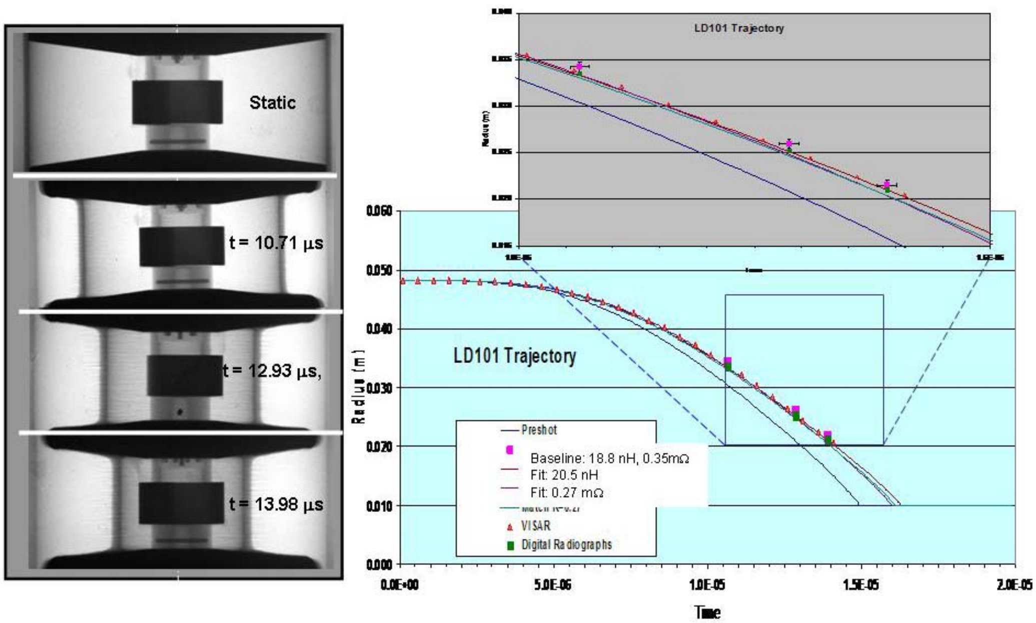

Figure 6. Liner dynamics were validated against zero dimensional (circuit) models using detailed laser interferometric (VISAR measurement of inner surface position.

stringent set of parameters against with to test circuit models. Not surprisingly it was found that circuit models provide adequate prediction of current delivery and implosion dynamics up to conditions in which magnetic fields on the liner surface or surrounding current carrying conductors approach 1 MG. Where fields approach or exceed megagauss level, additional complexity including 1-D MHD calculations of flux diffusion into surrounding conductors is necessary.

III. PULSED POWER HYDRODYNAMICS EXPERIMENTS

Liner-driven, pulsed power hydrodynamics techniques can be applied to a variety of interesting questions broadly addressing the properties and behavior of condensed matter and plasmas. Generally, these topics fall into three categories: (1) the properties of condensed matter at the extremes of pressure, temperature, and energy density[8]; (2) the hydrodynamic behavior of imploding systems[9]; and (3) the properties and behavior of dense plasmas.[10][11] In the first category, material properties, pulsed power driven liner experiments can explore the equation of state of materials and phase transitions under single shock (Hugoniot) conditions, ultimately at higher shock pressures than those attainable by gas-gun and flyer-plate techniques because higher impact velocities are possible. Magnetic implosions also offer shock-less compression capable of pushing materials to states not accessible through a single shock process (off-Hugoniot conditions). Liner implosions can drive materials to conditions of total strain and rate-of-strain far exceeding those available from other techniques, enabling the study of material strength and material failure at surfaces (ejecta) and in the bulk (spall), under unprecedented conditions. In the second category, implosion hydrodynamics, liner techniques have already been demonstrate for exploring instability growth in both full strength and strength-less materials, the behavior of material at interfaces (friction) and hydrodynamic flows in complex geometries. In the third category, plasmas in which the ion and electron physics are strongly coupled are difficult to produce and little experimental data are available. The extremely high liner implosion velocities accessible with magnetic drive can conceptually produce plasmas characterized as warm-dense matter. Realistically, only a limited number of these topics can be addressed simultaneously and those selected for early exploration on the Atlas facility included material strength and failure (spall), interfacial dynamics (friction), and specific problems in hydrodynamics.

Damaged Surface Hydrodynamics

A new experiment, introduced into the program at the NTS, explores the transport of material generically referred to as “ejecta”, produced when a shock emerges from the (inner) surface of a material (the liner) into a gas (prefill). This problem is important for a variety of liner compression applications such as those described in the third example in Figure 2. For a liner compressed (magnetized fusion) plasma, material ejected from the liner inner surface could significantly contaminate the plasma, enhancing radiation losses in a fusion context or substantially affecting the initial conditions of a warm, dense matter experiment. Figure 7 shows the conceptual

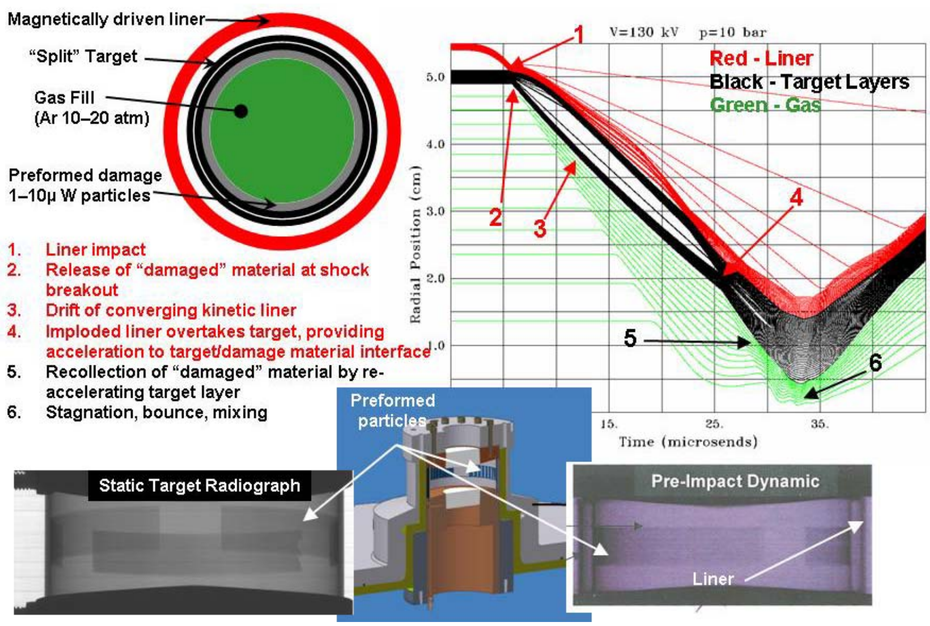

Figure 7. Conceptual design of the Damaged Surface Hydrodynamics Experiment. provide a reliable source of standardized and characterized “damaged” material.

design of the experiment which uses preformed (tungsten) particles attached to the material (liner) surface with a weak adhesive to provide a source of well characterized "damage" material. A magnetically imploded liner impacts a shock receiver, relatively early in the current waveform, initiating a relatively strong shock in the target and releasing the pre-formed "damage" material from the surface. The target is "split", comprised of a pair of concentric, close fitting, equal-mass aluminum cylinders. Upon impact of the liner, the inner and outer target layers separate and the inner layer with the particles moves inward, compressing the gas, while the outer layer and the liner come to a stop, conserving momentum. The outer target/liner ensemble is then reaccelerated by magnetic pressure from continuing current flow in the liner, eventually overtaking the inner target layer, and reaccelerating it as it approaches maximum compression. The continuous (and augmented) acceleration of the inner surface makes it possible to test some aspects of recollection of the particulate and potentially to explore how the "damaged" particles mix with the gas at maximum compression as the liner "bounces" off the compressed gas.

SUMMARY

The emerging field of Pulsed Power Hydrodynamics uses recent advancements in the area of ultra-low impedance, high current pulsed power to address applications in material properties, instabilities and turbulent mixing, and warm dense matter. The high precision, cylindrically imploded liner is, currently, the principle tool for converting electromagnetic energy to the hydrodynamic energy needed for the experiments. Early applications in the Atlas experimental series include material damage, advanced hydrodynamics, and interfacial dynamics.

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